

## **APPARATUS FOR SHAPING THE OUTPUT BEAM OF SEMICONDUCTOR LASERS**

### *Related Applications*

This application is related to, and claims the benefit of priority from, United States Provisional Patent Application Serial No. 60/410,212, filed September 12, 2003.

### *Field of the Invention*

The present invention relates to semiconductor lasers, including for example diode lasers arranged in arrays, and more particularly to an apparatus for shaping the collective output beam of such lasers in order to improve the beam quality by minimizing non-light-emitting areas.

### *Background*

Lasers have been around in one form or another for the past fifty years. More recently, semiconductor materials have come to be employed as a lasing medium. In semiconductor lasers generally, the requisite population inversion is established by pumping excess ions into the conduction band. Stimulated emission -- that is, lasing -- occurs as the electrons fall across the band gap.

High power diode lasers are one form of semiconductor laser which convert electrical energy into laser emissions -- that is, coherent light -- at a relatively high efficiency, typically greater than 50%. Typical individual diode lasers are approximately 10mm wide and approximately 0.1mm high. While such diode lasers operating singly emit about 50 watts (W) of continuous output power, this output can

be scaled upwardly into the kilowatt (kW) range by assembling individual diode lasers in a so-called stacked array.

Conventionally, a stacked array comprises several individual strips, or bars, of diode lasers arranged one on top of the other in the Y axis, with each bar in turn consisting of a linear series of individual diode lasers having their radiation-emitting openings arranged in a straight line and paralleling the same plane (X-Y) as the strips. A heat sink is commonly associated with each strip. In a typical diode laser array, individual diode lasers in a given strip are placed equidistant apart along a fixed-distance, for instance 10mm. Each individual diode laser in the strip is characterized, typically, by a light emitting area of about 2.0mm in the X axis, and about 0.001 in the Y axis. Typical divergence for these lasers is about 10 degrees full angle in the X axis, and about 90 degrees full angle in the Y axis. Thus, a single diode laser strip having a 10mm width exhibits an emitting area of about 10mm in the X axis and about 0.001 mm in the Y axis, with divergence of about 10 degrees in the X axis and about 90 degrees in the Y axis.

Their high conversion efficiency, as well as their relatively compact size and long operating life, make semiconductor lasers such as diode lasers an attractive choice for pumping-type solid-state lasers, such as Neodymium:Yttrium Aluminum Garnet (Nd:YAG) lasers, and for use in a variety of material processing applications, including, for example, surface heat treatment, laser cutting, laser welding, etc.

Despite their advantages, however, conventional diode lasers, particularly in the stacked array form, are characterized by limited beam quality and a highly asymmetric output beam. Importantly, these drawbacks prohibit focusing the laser output beam on a small focal point, a common requirement in material processing applications.

State of the art optical assemblies for symmetrizing the output beam and increasing brightness thereof employ refractive optical elements which section the output beam. This approach mandates very close manufacturing tolerances and precise assembly, in consequence of which such state of the art optical assemblies are high in cost.

It would therefore be desirable to provide for an optical assembly for shaping the output beam of one or more semiconductor lasers which is at once more economical to manufacture, and which overcomes other drawbacks found in conventional optical assemblies.

Summary of the Disclosure

The specification describes an apparatus for shaping part of the collective output beam of a plurality of semiconductor lasers, including a stacked array of such lasers, the plurality of semiconductor lasers being arranged to define a plurality of light-emitting areas and a plurality of non-light-emitting areas, and the semiconductor lasers having dimensions in X, Y and Z axes, wherein the Y axis defines a fast axis, the X axis defines a slow axis, and the Z axis defines an axis of propagation for the output beam. The inventive apparatus itself comprises a first reflective member comprising at least a first reflective element positioned a fixed distance from the semiconductor lasers, the at least first reflective element adapted to deflect a first portion of the output beam in a first direction oriented at a first angle in the slow axis direction and at a second angle in the fast axis direction; and at least a second reflective member comprising at least a first reflective element positioned a fixed distance from the semiconductor lasers, the at least first reflective element of the second reflective member adapted to deflect the first portion of the output beam from

the first direction to a second direction in the Z axis direction. By so shaping the collective output beam, the first portion of the output beam is oriented approximately parallel to the un-deflected remainder of the output beam, and the non-light-emitting areas are substantially eliminated from the output beam.

According to one embodiment of the present invention, the first reflective member further comprises a second reflective element positioned a fixed distance from the semiconductor lasers, the second reflective element adapted to deflect a second portion of the output beam in a third direction oriented at a third angle in the slow axis direction and at a fourth angle in the fast axis direction; and the at least second reflective member comprises a second reflective element positioned a fixed distance from the semiconductor lasers, the at least second reflective element of the second reflective member adapted to deflect the second portion of the output beam from the third direction to a fourth direction in the Z axis direction. According to this embodiment, the first and second portions of the output beam are oriented approximately parallel to each other and to the un-deflected remainder of the output beam, and the non-light-emitting areas are substantially eliminated from the output beam.

In one form of this embodiment, the third direction is approximately opposite the first direction, the first and third angles are approximately the same, the second and fourth angles are approximately the same, and the second and fourth directions are approximately the same.

According to yet another embodiment, the first reflective element is adapted to deflect a second portion of the output beam in a third direction oriented at a third angle in the slow axis direction and at a fourth angle in the fast axis direction; and the at least second reflective member comprises a second reflective element positioned a

fixed distance from the semiconductor lasers, the at least second reflective element of the second reflective member adapted to deflect the second portion of the output beam from the third direction to a fourth direction in the Z axis direction. Per this embodiment, the first and second portions of the output beam are oriented approximately parallel to each other and to the un-deflected remainder of the output beam, and the non-light-emitting areas are substantially eliminated from the output beam.

In one form of this embodiment, the third direction is approximately opposite the first direction, the first and third angles are approximately the same, the second and fourth angles are approximately the same, and the second and fourth directions are approximately the same.

In any of the foregoing embodiments, the invention may further comprise at least one optical member adapted to balance the optical path length of the un-deflected remainder of the output beam, the at least one optical member being disposed at a fixed position in the axis of propagation of the un-deflected remainder of the output beam.

The present invention is well suited to shaping the collective output beam of a stacked array of semiconductor lasers, and the invention, according to one feature thereof, comprises an apparatus for shaping part of the collective output beam of a plurality of semiconductor lasers comprising individual bars of semiconductor lasers stacked one on top of the other to form an array, the plurality of semiconductor lasers being arranged to define a plurality of light-emitting areas and a plurality of non-light-emitting areas, and the array having dimensions in X, Y and Z axes, wherein the Y axis defines a fast axis, the X axis defines a slow axis, and the Z axis defines an axis of propagation for the output beam. Per this feature, the inventive apparatus

particularly comprises a first reflective member comprising at least a first reflective element positioned a fixed distance from each bar in the array, the at least first reflective element adapted to deflect a first portion of the output beam from each bar in the array in a first direction oriented at a first angle in the slow axis direction and at a second angle in the fast axis direction; and at least a second reflective member comprising at least a first reflective element positioned a fixed distance from each bar in the array, the at least first reflective element of the second reflective member adapted to deflect the first portion of the output beam from each bar from the first direction to a second direction oriented in the Z axis direction. By so shaping the output beams of each bar in the array, the first portion of the output beams of each bar in the array are oriented approximately parallel to the un-deflected remainder of the output beams of each bar, and the non-light-emitting areas are substantially eliminated from the output beams.

In one embodiment of the inventive apparatus, the first reflective member further comprises a second reflective element positioned a fixed distance from each bar in the array, the second reflective element adapted to deflect a second portion of the output beam from each bar in a third direction oriented at a third angle in the slow axis direction and at a fourth angle in the fast axis direction; and the at least second reflective member comprises a second reflective element positioned a fixed distance from each bar in the array, the at least second reflective element of the second reflective member adapted to deflect the second portion of the output beam of each bar from the third direction to a fourth direction in the Z axis direction. Per this embodiment, the first portion and second portion of the output beams of each bar in the array are oriented approximately parallel to the un-deflected remainder of the output beams of each bar, and the non-light-emitting areas are substantially eliminated

from the output beams.

According to one aspect of this embodiment, the third direction is approximately opposite the first direction, the first and third angles are approximately the same, the second and fourth angles are approximately the same, and the second and fourth directions are approximately the same.

In yet another embodiment, the at least first reflective element is adapted to deflect a second portion of the output beam of each bar in a third direction oriented at a third angle in the slow axis direction and at a fourth angle in the fast axis direction; and the at least second reflective member comprising a second reflective element positioned a fixed distance from each bar in the array, the at least second reflective element of the second reflective member adapted to deflect the second portion of the output beam from the third direction to a fourth direction in the Z axis direction. Per this embodiment, the first portion and second portion of the output beams of each bar in the array are oriented approximately parallel to the un-deflected remainder of the output beams of each bar, and the non-light-emitting areas are substantially eliminated from the output beams.

According to one aspect hereof, the third direction is approximately opposite the first direction, the first and third angles are approximately the same, the second and fourth angles are approximately the same, and the second and fourth directions are approximately the same.

In any of the foregoing embodiments, the invention may further comprise at least one optical member adapted to balance the optical path length of the un-deflected remainder of the output beam of at least one bar in the array, the at least one optical member being disposed at a fixed position in the axis of propagation of the un-deflected remainder of the output beam.

According to one feature of the foregoing embodiments, the total height of the first and second reflective members corresponds to the pitch of the semiconductor lasers in the array.

According to another feature of the foregoing embodiments, the output beams of each bar in the array are propagated in a direction substantially perpendicular to a plane defined by the X and Y axes.

Per still another feature of this invention, the at least first element of the second reflective member comprises a monolithic element having a plurality of individual reflective portions each adapted to reflect a portion of the output beam of a discrete one of the bars in the array, and a plurality of cut-out portions defined between adjacent reflective portions, each cut-out portion adapted to permit transmission therethrough of a portion of the output beam of a discrete one of the bars in the array. The cut-out portions include opposing inside surfaces, each of which inside surfaces is oriented approximately parallel to the path of travel of the portion of the output beam transmitted therethrough. Per one aspect hereof, opposing inside surfaces of each cut-out portion include an anti-reflective coating.

#### *Brief Description of the Drawings*

The written description herein makes reference to the accompanying drawings, wherein like numerals refer to like or corresponding parts throughout the several views, and wherein:

**FIG. 1A** is a schematic view, taken along the Y axis, of one embodiment of the apparatus of the present invention, wherein the beam of a single, high power diode laser is shaped into three separate beams;



**FIG. 1B** is a schematic view of the embodiment of **FIG. 1A** taken along the X axis;

**FIG. 2** is a schematic view, taken along the Y axis, of a further embodiment of the apparatus of the present invention, wherein the laser beam of a single, high power diode laser is reconfigured into three separate beams, and the apparatus includes an optical member for balancing the path length of the separate beams;

**FIG. 3** is a schematic view, taken along the X axis, of a further embodiment of the apparatus of the present invention, wherein the laser beam of a stacked array of high power diode lasers is reconfigured into three separate beams;

**FIG. 4A** is a schematic view, taken along the Y axis, of another embodiment of the apparatus of the present invention, wherein the laser beam of a stacked array of high power diode lasers is reconfigured into four separate beams, and the beams are subsequently combined in two illuminated areas;

**FIG. 4B** is a schematic view of the embodiment of **FIG. 4A**, taken along the X axis;

**FIGS. 5A-5C** depict a first embodiment of the first reflective member of the apparatus of the present invention in, respectively, lateral, top-down, and end-view elevations;

**FIGS. 5D-5G** depict a first embodiment of the second reflective member of the apparatus of the present invention in, respectively, lateral, top-down, and end-view elevations, and in perspective view;

**FIG. 6A** is a schematic view, taken along the X axis, of a further embodiment of the apparatus of the present invention, wherein the laser beams of a stacked array of high power diode lasers, each having a different wavelength, is reconfigured into three separate beams which are subsequently combined in two illuminated areas;

**FIGS. 6B and 6C** each comprise schematic views, taken along the Y axis, of another embodiment of the apparatus of the present invention, wherein the laser beams of a stacked array of high power diode lasers, each having a different wavelength (one wavelength depicted in each figure), are arranged in alternating sequence, and the beams of each laser are reconfigured into three separate beams which are subsequently combined in two identical illuminated areas;

**FIG. 7** is a schematic view depicting one possible arrangement for multiplexing individual beams of the apparatus of the present invention into a single beam;

**FIG. 8A** depicts the near field of an exemplary set-up of a stacked array assembled with a symmetrizing element which creates four identical spots arranged equidistant in each of the fast and slow axis directions; and

**FIG. 8B** is a schematic view, taken along the X axis, of another embodiment of the apparatus of the present invention, wherein the laser beams of a stacked array of high power diode lasers are combined with a symmetrizing device which creates four identical spots arranged equidistant in both the fast and slow axis directions, as well as optical switches allowing independent power variations in each individual beam.

#### Written Description

With reference being had to the drawings, wherein like numerals indicate like or corresponding parts, the present invention will be seen to comprise an apparatus for shaping part of the output beam of a semiconductor laser, including in the form of an array of laser diodes, the semiconductor laser having dimensions in X, Y and Z axes, the Y axis defining a fast axis, the X axis defining a slow axis, and the Z axis defining an axis of propagation for the output beam. The inventive apparatus generally

comprises a first reflective member comprising at least a first reflective element positioned a fixed distance from the semiconductor laser, the at least first reflective element adapted to deflect a first portion of the output beam in a first direction and at a first angle in the slow axis direction and a second angle in the fast axis direction, and at least a second reflective member comprising at least a first reflective element positioned a fixed distance from the semiconductor laser, the at least second reflective element adapted to deflect the first portion of the output beam in a third direction in the Z axis direction so that the first portion of the output beam is oriented parallel to the un-deflected remainder of the output beam, and the non-light-emitting areas of the laser are substantially eliminated from the output beam.

Turning now to **FIGS. 1A** and **1B**, the inventive apparatus is shown in a first embodiment in combination with a semiconductor laser in the exemplary form of a single strip or bar **10** of high-power diode lasers having the output beam thereof collimated in the fast -- or Y -- axis, as well as, optionally, in the slow -- or X -- axis. A first reflective member comprises, in the illustrated embodiment, first and second reflective elements **20** and **40** positioned to deflect portions **50** and **70**, respectively, of the output beam. The beam portion **50** is deflected by the reflective element **20** in a direction along the slow axis towards a center, un-reflected portion **60** of the output beam at an angle of approximately 90 degrees, and is further deflected downwardly along the fast axis at an angle of approximately 5 degrees. The lateral beam **70** is similarly deflected by the reflective element **40**, though in the opposite direction in the X and Y axes.

A second reflective member comprises, in the illustrated embodiment, first and second reflective elements **31** and **32** positioned proximate the point of intersection of the beam portions **50** and **70**. A center portion **60** of the output beam is

transmitted through the first and second reflective elements **31** and **32** without being deflected thereby. As shown, the reflective element **31** deflects the beam portion **50** along the Z axis so that the beam portion **50** is parallel to the center beam portion **60** in each axis Y, Z, and at the same X coordinate. Likewise, the reflective element **32** deflects the beam portion **70** along the Z axis so that the beam portion **70** is parallel to the center beam portion **60** in each axis Y, Z.

It will be appreciated from this disclosure that the individual beam portions **50**, **60** and **70** may be defined at angles other than as shown in the exemplary illustrations, the deflection angles of the above-described embodiment being for illustrative purposes only and not intended to be limiting of the present invention. The beam quality as improved by the inventive apparatus will not be affected by different deflection angles, since the beams are reflected rather than refracted.

It will also be understood from this disclosure that the output beam of the semiconductor laser, including for example the diode laser of the illustrated embodiments, may be divided by the first reflective member into any number of separate beam portions ranging from two to more than eight beam portions, depending upon the particular application concerned; the three individual beam portions of the aforescribed embodiment are exemplary only.

Likewise, the laser beam output from the semiconductor laser need not be collimated at all, but may be shaped in other ways according to known means, all as necessitated by the particular application for the inventive apparatus.

Referring now to **FIG. 2**, which depicts schematically a further embodiment of the present invention shown, by way of example, in combination with the apparatus of **FIGS. 1A** and **1B**, it will be seen that the apparatus of this invention may further comprise an optical member **80** positioned along the path of the central beam portion

60 in order to balance the optical path length of the center beam portion 60 with that of the lateral beam portions 50 and 70. The optical member 80 may comprise any of the numerous forms of such devices known to those of skill in the art. Of course, the position of the optical member 80 is intended to be illustrative only, and other positions may be adopted as dictated by the particular application.

Turning next to **FIG. 3**, the embodiment of **FIGS. 1A** and **1B** is shown in combination with plural strips of diode lasers 10, 11, and 12 arranged as a stacked array. As with the embodiment of **FIGS. 1A** and **1B**, the output beam of each diode laser 10, 11, and 12 is collimated in the fast axis (Y), as well as, optionally, in the slow axis (X), and these collimated beams are divided into separate beam portions as follows: The output beam of diode laser 10 is divided into three separate beam portions 50, 60, and 70 by a first reflective member comprising first and second reflective elements 20 and 40, which first and second reflective elements each deflect a beam portion 50 or 70, respectively, in a direction along the slow axis towards a center, un-reflected beam portion 60 of the output beam at an angle of approximately 90 degrees, and which further deflect these beam portions 50 and 70 downwardly along the fast axis at an angle of approximately 5 degrees. The center beam portion 60 is transmitted through the first and second reflective elements 30 and 31 of the second reflective member without being deflected thereby. The intersecting lateral beam portions 50 and 70 are deflected by the first and second elements 30 and 31, respectively, of the second reflective member in both of the slow and fast axes so as to be parallel to the center beam 60 in each of the Y and Z axes, all as described above in more detail with reference to **FIGS. 1A** and **1B**. The output beam of diode laser 11 is similarly divided into separate beam portions 51 and 71 by a first reflective member comprising first and second reflective elements 21 and 41, and the intersecting lateral

beam portions **51** and **71** are deflected along the *Z* axis by a second reflective member comprising reflective elements **32** and **33** so as to be parallel to a center, un-deflected beam portion **60** in each of the *Y* and *Z* axes. Likewise, the output beam of diode laser **12** is divided into separate beams **52** and **72** by a first reflective member comprising first and second reflective elements **23** and **42**, and the intersecting lateral beam portions **52** and **72** are deflected along the *Z* axis by a second reflective member comprising first and second reflective elements **34** and **35** so as to be parallel to an un-deflected center beam portion **60** in each of the *Y* and *Z* axes.

The individual beam portions **50**, **60**, **70**, and **51**, **61**, **71**, and **52**, **62**, **72** of each diode laser **10**, **11** and **12**, respectively, are all placed in close proximity one on top of the other in the fast (*Y*) axis direction, as shown, so as to emerge along the *Z* axis parallel to each other and perpendicular to a plane defined by the fast (*Y*) and slow (*X*) axes of each diode laser **10**, **11** and **12**.

The individual reflective elements **20**, **21**, **22**, **40**, **41**, and **42** of the first reflective member, as well as the individual reflective elements **31**, **32**, **33**, **34**, and **35** of the second reflective member, may each be manufactured from individual optical elements stacked on top of each other or, alternatively, may be optically bonded or made from a single component, depending upon such considerations as the particular design of the laser and the number of individual beams. Suitable materials for these reflective elements are known to those skilled in the art and may, for example, comprise glass or metal that is polished and shaped. The reflective elements are preferably affixed to a base plate (not shown) having, as desired, means for efficient heat dissipation, such as micro-channels for passing a forced liquid coolant.

Ideally, the first and second reflective members associated with each diode laser **10**, **11**, and **12** are characterized by a total height corresponding to the pitch of

the collimated diode lasers **10**, **11** and **12**.

It will be appreciated from this disclosure that each collimated diode laser may be split in a different number of individual beam portions to balance the resulting beam height of the individual beams placed on top of each other in the slow (X) axis direction with the pitch of the diode lasers of the stacked array. It will also be understood that while the individual beams emerge both parallel and in close proximity to each other in the fast (Y) axis after being deflected by the reflective elements of the second reflective member, they may also be deflected to emerge under an angle with respect to the plane defined by the slow and fast axes of the diode lasers.

With reference now being had to **FIGS. 4A** and **4B**, a further embodiment of the present invention is shown in which the output beam of a stacked array of semiconductor lasers, such as the illustrated diode laser bars (only the top-most laser bar **100** is visible in **FIG. 4A**, which is taken along the Y axis; that is, showing the X-Z plane), is divided into multiple separate beam portions.

With specific reference to **FIG. 4A**, it may be seen that for each diode laser two separate beam portions **150** and **160** are defined by means of a first reflective member comprising a first reflective element **120**. More particularly, the reflective element **120** will be seen to split the output beam into separate beam portions **150** and **160**, with beam portion **150** being deflected in a first direction and beam portion **160** being deflected oppositely in a second direction. As illustrated, the beam portions **150** and **160** are deflected oppositely in the slow (X) axis direction at identical angles relative to the reflective surface of the reflective element **120**.

Still referring to **FIG. 4A**, a second reflective member comprises first and second reflective elements **110** and **130**, each being positioned proximate the

intersections of, respectively, the un-deflected lateral beam portions **140** and **170** and the deflected lateral beam portions **160** and **170**. The lateral beam portions **140** and **170** are un-deflected by the respective reflective elements **110** and **130** of the second reflective member, though it will of course be understood by those skilled in the art that the width of the beam portions **150** and **170** will necessarily be affected by the placement of the first reflective element **120** in the propagation path of these beam portions. The first reflective element **110** serves to deflect the beam portion **150** to emerge parallel to the lateral beam portion **140** in both the Y and Z axes, the beam portions **150** and **140** having the same coordinate position along the X axis. Similarly, the second reflective element **130** serves to deflect the beam portion **160** to emerge parallel to the un-reflected lateral beam portion **170** in both the Y and Z axes, the beam portions **160** and **170** having the same coordinate position along the X axis.

By operation of the first and second reflective members, as hereinabove described, the individual beam portions **150** and **160** are combined with the lateral beam portions **140** and **170** to define a pair of beams **180** and **190**, respectively. (FIG. 4A.) The beams **180** and **190** are of identical dimensions and beam quality, and are further characterized in that the center of each of the beams **180** and **190** are precisely parallel to each other in both the slow (X) and fast (Y) axes, as well as being equidistant from a centerline defined parallel to the direction of propagation (Z-axis) and intersecting the X-Y plane at the center of the diode laser **100**. By virtue of the shaping of the output beam according to this invention, the two beams **180** and **190** show minimized non-light-emitting area between the individual constituent beam portions **140** and **150** or **160** and **170**, respectively.

Though not shown in FIGS. 4A and 4B, means for balancing the optical path lengths of the several beams, such as described in connection with the embodiment of



**FIG. 2**, may also be employed. These means may comprise separate optical elements, or may be formed as part of a single structure further comprising the first and second reflective members.

With particular reference to **FIG. 4B**, wherein the embodiment of **FIG. 4A** is shown in conjunction with multiple semiconductor lasers **101** and **102** assembled in a stacked array, the stacked array diode laser is shown to comprise two collimated diode lasers **101** and **102**, the beam of each laser being divided into four separate beams portions **141**, **151**, **161**, and **171** or **142**, **152**, **162**, or **172**, respectively. The first reflective members associated with each diode laser **101** or **102** and comprising, respectively, reflective elements **121** and **122**, are oriented in the slow (X) axis in the same manner as that shown in **FIG. 4A** with reference to the reflective element **120**, as are the second reflective members associated with each diode laser **101** and **102** and comprising, respectively, first and second reflective elements **111** and **131** or first and second reflective elements **112** and **132**. In each diode laser assembly **101** or **102**, the individual beam portions **151** and **161** or **152** and **162**, respectively, are deflected by the reflective elements of the aforementioned first and second reflective members in the manner described with reference to **FIG. 4A**, and emerge, in combination with the un-deflected lateral beam portions **141** and **171** or **142** and **172**, respectively, as pairs of beams; particularly, the beams emerging from the laser diode assembly **101** comprise beams **181** and **191**, made up, respectively, of beam portions **141**, **171** and **151**, **161**; the beams emerging from the laser diode assembly **102** comprise beams **182** and **192**, made up, respectively, of beam portions **142**, **172** and **152**, **162**. These light-emitting areas are precisely aligned in all axes.

With continuing reference to **FIG. 4B**, it will be appreciated that multiple collimated diode lasers may be arranged one on top of the other at a specific pitch in

order to scale the output power and symmetrize the beam quality of the emerging beams **181,190** and **182,192** in a laser array. The number of individual beam portions (e.g., **141, 151, 161, 171**) is determined by matching the beam height of each of the beams **181,190** and **182,192** with the pitch of the stacked array comprising diode lasers **101** and **102** such that all non-light-emitting areas between the adjacent diode lasers **101** and **102** are eliminated in the fast (Y) axis. Therefore, the number of individual beam portions is calculated as the ratio of the beam height of the beams **181,190** and **182,192** and the beam height of the collimated diode lasers **101** and **102**. By way of illustration, the beam height in the fast (Y) axis of a stacked array having a pitch of 2.0mm would, likewise, be 2.0mm. And assuming a beam height of 1.0mm for each diode laser **101** and **102**, then two individual beams (e.g., **181,190**) may be arranged one on top of the other in the fast axis direction for each diode laser **101** and **102** with no non-light-emitting areas in between them.

In the slow (X) axis direction the beam quality of the light-emitting areas comprising beams **181, 182, 191** and **192** is determined by the number of individual beam portions, as well as the width and slow axis divergence of the diode lasers **101** and **102**. For instance, a slow axis divergence after collimation of 80 mrad full angle and a width of the diode laser of 10 mm yields a beam parameter product in the slow axis of 200 mm\*mrad. If the radiation of the diode lasers **101** and **102** are each divided in four separate beam portions combined into two light-emitting areas (e.g., **181** and **191** or **182** and **192**), a beam parameter product of the individual beams in the slow axis of 50 mm\*mrad will result for each light-emitting area.

In the fast (Y) axis the beam quality is determined by the number of individual beam portions comprising the light-emitting areas of beams **181** and **191** or **182** and **192**, respectively, and the divergence of the collimated diode lasers **101** and **102**. For

example, a fast axis divergence after collimation of 8 mrad full angle and a beam height of 1 mm results in a beam parameter product in the fast axis of 2 mm\*mrad for the collimated diode lasers 101 and 102. In the illustrated embodiment, the diode lasers 101 and 102 are divided into four separate beam portions each of which are combined into pairs of beams (181 and 191 or 182 and 192, respectively), with beam portions, 141, 171, or 151,161, or 142,172, or 152,162 being arranged on top of each other in the fast axis in each of beams 181, 191, 182, or 192, respectively. Consequently, the beam parameter product in the fast axis direction of the diode lasers 101 and 102 are 4 mm\*mrad each, or 8 mm\*mrad combined.

The beam quality of the light-emitting beam areas emerging from the first and second reflective members can be designed to balance in both of the fast (Y) and slow (X) axes. Thus, for instance, in the exemplary arrangement the number of diode lasers that must be stacked on each other in an array to achieve a beam parameter product of 50 mm\*mrad in both the fast and slow axes would be 12.5.

It will of course be understood that the pitch, beam height, and divergences of the collimated diode lasers may vary with different applications and, accordingly, that the number of individual beams may likewise be varied. It will likewise be appreciated that a diode laser array incorporating the apparatus of this invention may be designed so that the beam quality of the light-emitting beam areas is not balanced in the slow and fast axes, and that more than two such light-emitting beam areas may emerge. And while the light-emitting beam areas are always aligned in all axes, the respective center beam portions need not always emerge parallel to each other in the slow and fast axes, but may instead be displaced by a predetermined amount.

As discussed, the first and second reflective members of the several embodiments of the present invention, each comprising at least one reflective

element, may be monolithic or may, alternatively, be made from multiple individual elements. These reflective elements are ideally shaped as a prism or as a thin plate. For monolithic construction, by way of example, a single glass prism with highly polished surfaces may be employed.

The reflective surfaces of the reflective elements are polished to optical quality and coated with a highly reflective material to minimize transmission loss, all according to known methods. As necessary to permit the transmission of beam portions not intended to be deflected, the reflective elements may comprise both reflective and transmissive sections, being coated, for instance, with alternating sections of reflective and anti-reflective materials. Alternatively, the reflective elements may comprise only a reflective coating, while the anti-reflective sections may be achieved by removing substrate as necessary from the reflective elements to permit transmission of any beam portions not intended to be deflected. Furthermore, the functional surfaces of the reflective elements may be coated completely with an antireflective coating that is selectively covered by a high-reflective coating to provide the deflection where required.

Employing monolithic reflective elements in the apparatus of the present invention, the beams of all diode lasers in a single stacked array will be deflected precisely the same direction, and any misalignment of the emerging combined beams will be limited to that attributable to the manufacturing tolerances of relatively large optical components.

Alternatively, the first and second reflective elements may be manufactured from a unitary structure comprising a pair of glass plates having alternating sections of high transmission and reflective coatings that are inclined in the slow and fast axes relative to the plane defined by the slow (X) and fast (Y) axes. According to this

embodiment, the glass plates may be optically bonded.

Since the deflection angles are identical for all collimated diode lasers in a single stacked array, the inclination of the optical surfaces in the reflective elements is identical for all diode lasers in the array. On the other hand, the distance between the individual diode lasers and the optical surfaces will change if the reflective elements are monolithic. The reflective elements thus represent a plano-parallel glass plate having varying reflectivity in an alternating sequence from high reflectivity to high transmission.

The inclination angle of any given reflective element should be limited in the fast (Y) axis direction to small values to minimize the resulting astigmatism in subsequent focusing optics between the diode lasers in a single stacked array. The inclination in the fast axis defines the inclination in the slow (X) axis for a given pitch of the stacked array, as well as the distance between the first and second reflective optical elements.

**FIGS. 5A-5G** illustrate representative embodiments of the reflective elements of the first and second reflective members, particularly as they are incorporated in the embodiment of the inventive apparatus shown (schematically) and described in relation to **FIGS. 4A-4C**.

Referring specifically to **FIGS. 5A-5C**, an exemplary reflective element comprising the first reflective member is shown in various elevations to take the form of a fused silica prism including reflective surfaces **S1** and **S2** each having a high-reflective coating (800-880nm or 910-980nm, for example).

Turning now to **FIGS. 5D-5G**, an exemplary reflective element comprising the first of a pair of such elements forming the second reflective member is shown, the corresponding but oppositely (in the X axis) positioned second reflective element

of the second reflective member of this embodiment being similar in all material respects except as otherwise noted. The reflective element of this embodiment takes the form of a “comb” characterized by a plurality of spaced-apart “tines” **T** arranged seriatum in the Y axis and separated by cut-out portions **P**. As shown, the number of cut-out portions **P** and tines **T** provided in the illustrated embodiment is adapted for a 21-bar type stacked array of diode lasers. Each tine **T** is dimensioned to deflect, in the manner heretofore described, a portion of the output beam of a single diode laser in a stacked array. The “comb” is formed of fused silica, and includes a reflective surface **S1** having a high-reflectivity coating (800-880nm or 910-980nm, for instance), and an exemplary surface flatness of  $\lambda/4$  at 633nm. The cut-out portions **P**, each dimensioned to permit the transmission therethrough of a portion of the output beam of one of the diode lasers in a stacked array, have anti-reflective coated surfaces **P1**, **P2**, and **P3** oriented transverse to the reflective surface **S1**. In the embodiment of the illustrated example, the distance between adjacent cut-out portions **P** is approximately 2mm, with each cut-out portion **P** having a width of approximately 1mm. Relative to the reflective surface **S1**, the surfaces **P1** and **P2** of each cut-out portion **P** are oriented at an angle of approximately 6.2 degrees, such that, when the reflective element is properly inclined relative to the diode laser array, the surfaces **P1** and **P2** of each cut-out portion are oriented parallel to the path of travel of the un-deflected beam portions. In the second reflective element (not shown) comprising the second reflective member, the surfaces **P1** and **P2** of the cut-out portions **P** are oriented at an angle of approximately 6.2 degrees relative to the surface **S2** opposing the reflective surface **S1**, since the second reflective element is oppositely inclined relative to the first reflective element.

Of course, it will be understood that the reflectivity of any coating applied to

the first and second reflective members, including in the particular embodiments herein described, may be varied according to the application, and the specific coatings described in this specification are not intended to be limiting of this invention.

With reference now to **FIGS. 6A-6C**, a further embodiment of the present invention is shown in combination with a stacked array of diode lasers **201** and **202** having specific, though different, emission wavelengths, the diode lasers **201** and **202** arranged in a specific alternating sequence. According to this embodiment, the first and second reflective members are arranged such that the output beam of the individual diode lasers **201** and **202** are split into an identical number of separate, identical beams, with all such beams of the same wavelength being combined into a common emitting area.

More particularly, a stacked array is shown in schematic view to comprise, for example, two diode lasers **201** and **202**, each laser characterized by a different wavelength. **FIG. 6A**. With particular reference to **FIGS. 6B** and **6C**, the output beam of the diode laser **201** is divided into separate beam portions **251**, and **261** by a first reflective member comprising first and second reflective elements **221a** and **221b**. These beam portions **251** and **261** are deflected at a first angle in the slow axis direction, and at a second, downward (in the fast axis) angle by these reflective elements **221a**, **221b**. The separate beam portions **251** and **261** are subsequently deflected by a second reflective member comprising first and second reflective elements **211a** and **211b**. An un-deflected beam portion **241** passes the reflective elements **221** and **221b** without being deflected, and is, as shown, positioned above the beams **251** and **261**. The beam portions **261** and **251** are deflected by the first and second reflective elements **211a** and **211b**, respectively, to a path along the Z axis parallel to the beam portion **241** and in close proximity with each other in the fast axis

direction, and with no displacement in the slow axis. Accordingly, a light emitting area is created by this alignment of the beam portions **241**, **251**, and **261** which is characterized by a single wavelength, increased symmetry of beam quality in the slow (X) and fast (Y) axes, and no non-light emitting areas.

In similar fashion to that already described, the output beam of the second diode laser **202** is divided into three separate beam portions **242**, **252**, and **262** oriented into a single light emitting area also characterized by a single wavelength, increased symmetry of beam quality in the slow and fast axes, and no non-light emitting areas. As shown in **FIG. 6A**, the distinguishing feature of the beam shaping of the second diode laser **202** is that the beam portions **242** and **252** are deflected at an angle upwardly along the fast axis so as to be arranged above the un-deflected beam portion **262**.

It will be appreciated from the foregoing that this embodiment of the present invention creates two identical emitting areas, each having a different wavelength, wherein the center beams are precisely aligned in all axes.

Though the shaping of the output beams of just two diode lasers is shown, it will be understood that any number of diode lasers, or other semiconductor laser, having any number of different wavelengths may be arranged in a specific alternating way in a single stacked array, and further that the number of individual beams into which the output beam of each such laser is shaped may likewise be varied, all depending upon the required brightness of the array.

Turning now to **FIG. 7**, an exemplary arrangement is shown, schematically, for combining the multiple emitting beam areas **280** and **290** of a single stacked array, for instance the stacked array of **FIGS. 6A-6C**, into a single emitting area **300** by means of, for example, conventional techniques for polarizing or wavelength



multiplexing. Alternatively, the two emitting beam areas **280** and **290** may be arranged on top of each other in the fast (Y) axis by means of reflective or refractive optical elements.

Those skilled in the art will appreciate that one or more of the foregoing means may be employed, singly or in combination, to combine multiple emitting areas into a single emitting area, and that the particular arrangement employed depends upon the particular requirements for output power and beam quality.

With reference now being had to **FIG. 8A**, there is shown the optical near field of a stacked array incorporating the first and second reflective members of any of the embodiments of the invention as described herein, these first and second reflective members being arranged to produce four identical emitting beams areas **501**, **502**, **503**, and **504**, all spaced equidistant from each other, and in precise parallel alignment, in both the fast (Y) and slow (X) axes. Depending upon the composition of the stacked array, the beams **501**, **502**, **503**, and **504** may be characterized by the same or different wavelengths, and may further have one or multiple polarizations.

Referring now to **FIG. 8B**, each of the beams may pass an optical switch, as exemplified by the optical switches **601** and **603** shown for beams **501** and **503** in the view of an exemplary stacked array taken along the slow (X) axis, such that the output power of each beam may be independently varied. In combination with the precise alignment of the separate beams in six axes, it will be appreciated that the embodiment described herein is well suited for use in a dot matrix printing device, for example.

Still referring to **FIG. 8B**, the individual beams may further be shaped by optical elements, such as optical elements **701** and **703** shown in the path of beams **501** and **503**, for imaging on a work-piece or coupling into a fiber array, for instance,

according to conventional means.

Of course, the foregoing is merely illustrative of the present invention according to several embodiments thereof. Those of ordinary skill in the art will appreciate that many additions and modifications to the present invention, as set out in this disclosure, are possible without departing from the spirit and broader aspects of this invention as defined in the appended claims.